Figure IV-3-21. Ocean City Inlet, Maryland, 11 September 1995. Before the 1933 hurricane breached the barrier island, Assateague and Fenwick Islands were joined and had a straight shoreline. The former shoreline ran approximately along the seaward-most road (Photograph provided by USAE District, Baltimore)

- The *flood ramp*, which is a seaward-dipping sand surface dominated by flood-tidal currents. Sediment movement occurs in the form of sand waves (dunes), which migrate up the ramp.

- *Flood channels*, subtidal continuations of the flood ramp.

- The *ebb shield*, the high, landward margin of the tidal delta that helps divert ebb-tide currents around the shoal.

- *Ebb spits*, high areas mainly formed by ebb currents with some interaction with flood currents.

- *Spillover lobes*, linguoid, bar-like features formed by ebb-tidal current flow over low areas of the ebb shield.

(b) Although this model was originally derived from studies in mesotidal, mixed-energy conditions, it is also applicable to more wave-dominated, microtidal inlets (Boothroyd 1985). However, flood-tide shoals apparently are not formed in macrotidal shores.

(c) The high, central portion of a flood-tidal delta often extends some distance into an estuary or bay. This is the oldest portion of the delta and is usually vegetated by marsh plants. The marsh cap extends up to the elevation of the mean high water. The marsh expands aerially by growing out over the adjacent tidal flat. The highest, marsh-covered part of a flood shoal, or sometimes the entire shoal, is often identified on navigation charts as a "middle ground."

(3) Bed forms.

(a) Inlets contain a broad range of bed forms, from ripples due to oscillatory waves to dunes and antidunes caused by tidal currents. Water mass stratification can influence inlet flow and, therefore, bed form orientation. When a lagoon contains brackish water, salt wedge dynamics can occur, where the incoming flood flows under less dense bay water. Mixing between the two waters occurs along a horizontal density interface. During ebb tide, a buoyant planar jet forms at the seaward opening of the inlet similar to the effluent from rivers.

(b) Wright, Sonu, and Kielhorn (1972) described how density stratification affected flow at the Gulf of Mexico and Choctawhatchee Bay openings of East Pass, Florida. During flood tide, drogues and dye showed that the incoming salty Gulf of Mexico water met the brackish bay water at a sharp density front and then dove underneath (Figure IV-3-22). The drogues indicated that the sea water intruded at least 100 m beyond the front into Choctawhatchee Bay. This was the reason that bed forms within the channels displayed a flood orientation over time. This flood orientation can be seen in aerial photographs (Figure IV-3-5).

f. Inlet stability and migration.[1]

(1) Background. Inlets migrate along the coast - or remain fixed in one location - because of complex interactions between tidal prism, wave energy, and sediment supply. Some researchers consider the littoral system to be the principal sediment source that influences the stability of inlets (Oertel 1988). Not all of the sediment in littoral transport is trapped at the mouths of inlets; at many locations, a large proportion may be bypassed by a variety of mechanisms. Inlet sediment bypassing is defined as "the transport of sand from the updrift side of the tidal inlet to the downdrift shoreline" (FitzGerald 1988). Bruun and Gerritsen (1959) described three mechanisms by which sand moves past tidal inlets:

- Wave-induced transport along the outer edge of the ebb delta (the terminal lobe).
- The transport of sand in channels by tidal currents.
- The migration of tidal channels and sandbars.

They noted that at many inlets, bypassing occurred through a combination of these mechanisms. As an extension of this earlier work, FitzGerald, Hubbard, and Nummedal (1978) proposed three models to explain inlet sediment bypassing along mixed-energy coasts. The models are illustrated in Figure IV-3-23 and are discussed below.

[1] Material in this section has been adapted from FitzGerald (1988).

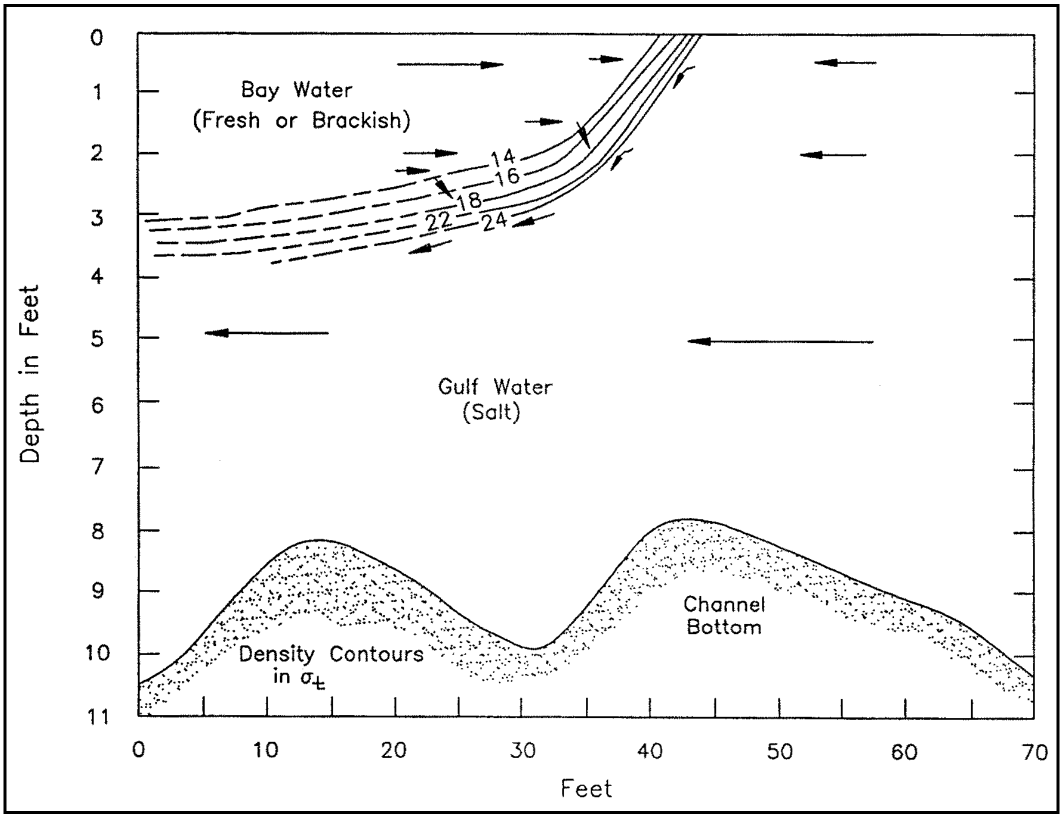

Figure IV-3-22. At the bay opening of East Pass, Florida, stratified flow occurs during flood tide in Choctawhatchee Bay as a wedge of sea water dives underneath the lower density bay water (after Wright, Sonu, and Kielhorn (1972)). A similar phenomenon often occurs in estuaries

(2) Inlet migration and spit breaching.

(a) The first model describes the tendency of many inlets to migrate downdrift and then abruptly shift their course by breaching a barrier spit. The migration occurs because sediment supplied by the longshore current causes the updrift barrier to grow (spit accretion). The growth occurs in the form of low, curved beach ridges, which weld to the end of the spit, often forming a bulbous-tipped spit known as a "drumstick." The ridges are often separated by low, marshy swales. As the inlet becomes narrower, the opposite (downdrift) shore erodes because tidal currents attempt to maintain an opening.

(b) In environments where the back bay is largely filled with marshes or where the barrier is close to the mainland, migration of the inlet causes an elongation of the tidal channel. Over time, the tidal flow between bay and ocean becomes more and more inefficient. Under these conditions, if a storm breaches the updrift barrier, the newly opened channel is a more direct and efficient pathway for tidal exchange. This new, shorter channel is likely to remain open while the older, longer route gradually closes. The breaching is most likely to occur across an area where the barrier has eroded or where some of the inner-ridge swales have remained low. The end result of spit accretion and breaching is the transfer of large quantities of sediment from one side of the inlet to the other. An example of this process is Kiawah River Inlet, South Carolina, whose migration between 1661 and 1978 was documented by FitzGerald, Hubbard, and Nummedal (1978). After a spit is breached and the old inlet closes, the former channel often becomes an elongated pond that parallels the coast.

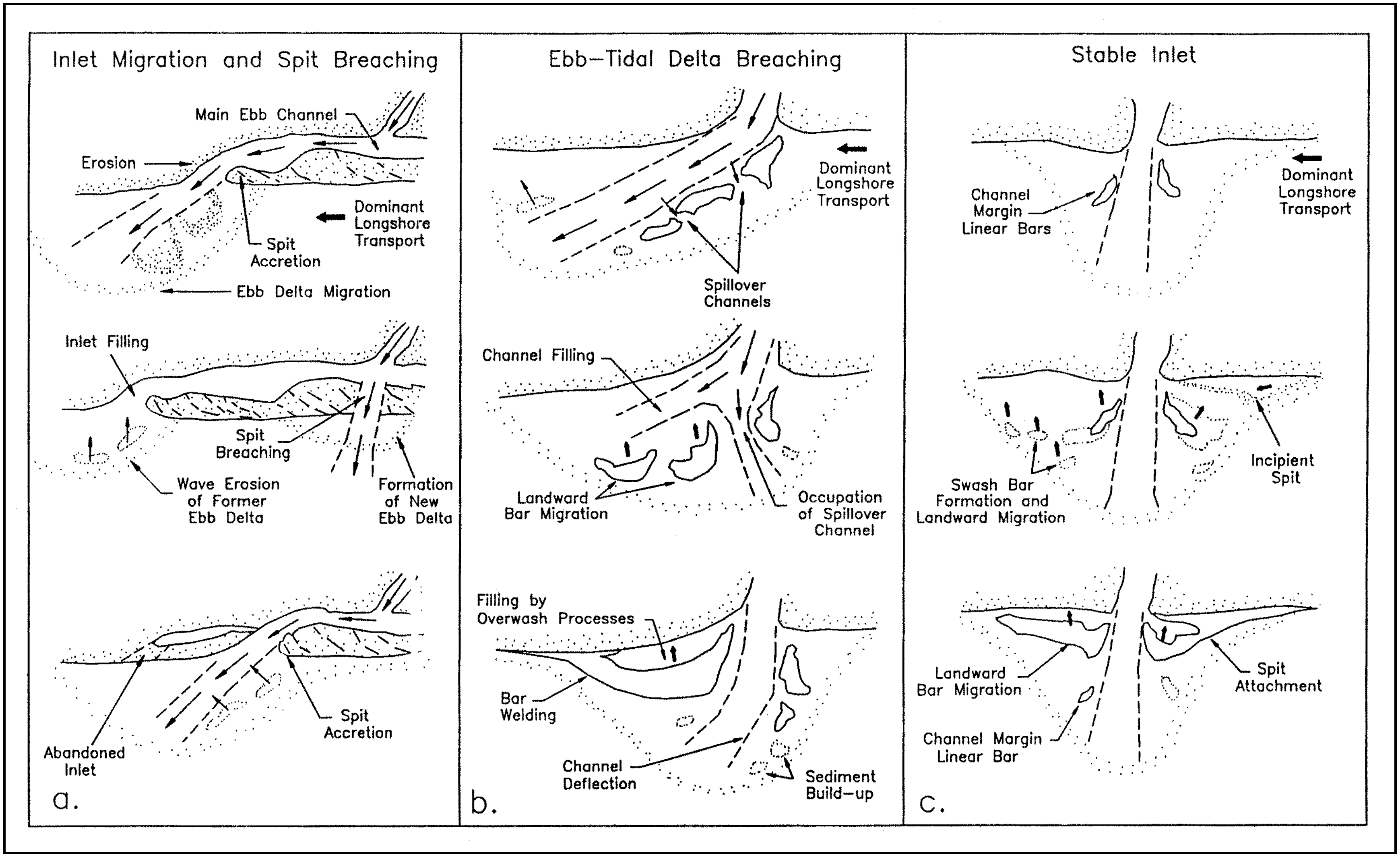

Figure IV-3-23. Three models of inlet behavior and sediment bypassing for mixed-energy coasts (from FitzGerald (1988))

(c) Several notes apply to the inlet migration model: First, not all inlets migrate. As discussed earlier, some inlets on microtidal shores are ephemeral, remaining open only a short time after a hurricane forces a breach through the barrier. If the normal tidal prism is small, these inlets are soon blocked by littoral drift. Short-lived inlets were documented along the Texas coast by Price and Parker (1979). The composition of the banks of the channel and the underlying geology are also critical factors. If an inlet abuts resistant sediment or bedrock, migration is restricted (for example, Hillsboro Inlet, on the Atlantic coast of Florida, is anchored by rock reefs). The gorge of deep inlets may be cut into resistant sediment, which also will restrict migration.

(d) Second, some inlets migrate updrift, against the direction of the predominate drift. Three mechanisms may account for updrift migration (Aubrey and Speer 1984):

- Attachment of swash bars to the inlet's downdrift shoreline.
- Breaching of the spit updrift of an inlet.
- Cutbank erosion of an inlet's updrift shoreline caused by back-bay tidal channels that approach the inlet throat obliquely.

(3) Ebb-tidal delta breaching.

(a) At some inlets, the position of the throat is stable, but the main ebb channel migrates over the ebb delta (Figure IV-3-23b). This pattern is sometimes seen at inlets that are naturally anchored by rock or have been stabilized by jetties. Sediment supplied by longshore drift accumulates on the updrift side of the ebb-tidal delta, which results in a deflection of the main ebb channel. The ebb channel continues to deflect until, in some cases, it flows parallel to the downdrift shore. This usually causes serious beach erosion. In this orientation, the channel is hydraulically inefficient, and the flow is likely to divert to a more direct seaward route through a spillover channel. Diversion of the flow can occur gradually over a period of months or can occur abruptly during a major storm. Eventually, most of the tidal exchange flows through the new channel, and the abandoned old channel fills with sand.

(b) Ebb delta breaching results in the bypassing of large amounts of sand because swash bars, which had formerly been updrift of the channel, become downdrift after the inlet occupies one of the spillover channels. Under the influence of waves, the swash bars migrate landward. The bars fill the abandoned channel and eventually weld to the downdrift beach.

(4) Stable inlet processes.

(a) These inlets have a stable throat position and a main ebb channel that does not migrate (Figure IV-3-23c). Sand bypassing occurs by means of large bar complexes that form on the ebb delta, migrate landward, and weld to the downdrift shoreline. The bar complexes are composed of swash bars that stack and merge as they migrate onshore. Swash bars are wave-built accumulations of sand that form on the ebb delta from sand that has been transported seaward in the main ebb channel. The swash bars move landward because of the dominance of landward flow across the swash platform. The reason for landward dominance of flow is that waves shoal and break over the terminal lobe (or bar) that forms along the seaward edge of the ebb delta. The bore from the breaking waves augments flood tidal currents but retards ebb currents.

(b) The amount of bypassing that actually occurs around a stable inlet depends upon the geometry of the ebb-tidal shoal, wave approach angle, and wave refraction around the shoal. Three sediment pathways can be identified:

- Some (or possibly much) of the longshore drift accumulates on the updrift side of the shoal in the form of a bar that projects out from the shore (Figure IV-3-23c). As the incipient spit grows, it merges with growing bar complexes near the ebb channel. Flood currents move some of the sand from the complexes into the ebb channel. Then, during ebb tide, currents flush the sand out of the channel onto the delta (both the updrift and downdrift sides), where it is available to feed the growth of new swash bars.

- Depending on the angle of wave approach, longshore currents flow around the ebb shoal from the updrift to the downdrift side. Some of the drift is able to move past the ebb channel, where it either continues moving along the coast or accumulates on the downdrift side of the ebb shoal. The sediment probably moves as large bed forms (Figure IV-3-4).

- Wave refraction around some ebb shoals causes a local reversal of longshore current direction along the downdrift shore. During this time, presumably, little sediment is able to escape the confines of the ebb-tidal shoal.

(5) Extension of bypassing models to other environments. The inlet migration models described above were originally based on moderate- to high-energy shores. However, research along the Florida Panhandle suggests that the models may be applicable to much lower energy environments than the original authors had anticipated. For example, between 1870 and 1990, the behavior of East Pass inlet, located in the low-wave-energy Florida Panhandle, followed all three models at various times (Figure IV-3-24; Morang (1992b)). It would be valuable to conduct inlet studies around the world to further refine the models and evaluate their applicability to different shores.

g. Inlet response to jetty construction and other engineering activities.

(1) Introduction. Typically, jetties are built to stabilize a migrating inlet, to protect a navigation channel from waves, or to reduce the amount of dredging required to maintain a specified channel depth. However, jetties can profoundly affect bypassing and other processes at inlets. Some of these effects can be predicted during the design phase of a project. Unfortunately, unanticipated geological conditions often arise, which lead to problems such as increased shoaling or changes in the tidal prism. Several classes of man-made activities affect inlets:

(a) Jetties stabilize inlets and prevent them from migrating.

(b) Jetties can block littoral drift.

(c) Walls or revetments can change the cross section of an inlet.

(d) Dredging can enlarge the cross section of a gorge.

(e) Dam construction and freshwater diversion reduce fluvial input.

(f) Weir sections (low portions of a jetty) allow sediment to pass into an inlet, where it can accumulate in a deposition basin and be bypassed.

(g) Landfilling and development in estuaries and bays can reduce tidal prism.

(2) Technical literature. Many reports have documented the effects of jetties on littoral sediment transport. Early works are cited in Barwis (1976). Dean (1988) discussed the response of modified Florida inlets,

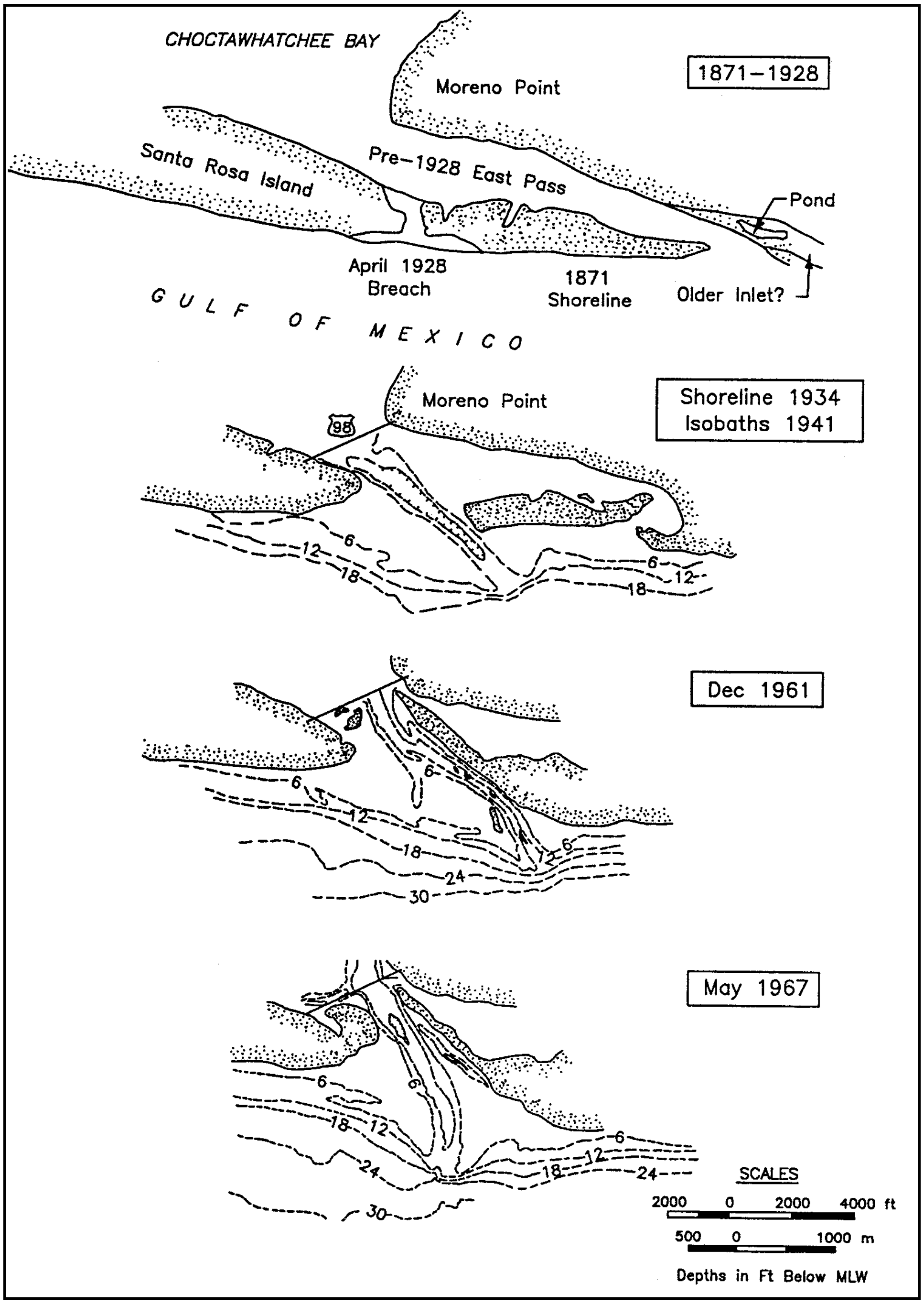

Figure IV-3-24. Spit breaching and inlet migration at East Pass, Florida (from Morang (1992a))

and many other case studies are reviewed in Aubrey and Weishar (1988). Examples of monitoring studies that assess the effects of jetties include:

(a) Shinnecock Inlet, Long Island, New York (Morang, 1999; Pratt and Stauble 2001; Williams, Morang, and Lillycrop 1998)

(b) Ocean City Inlet, Maryland (Bass et al. 1994).

(c) Little River Inlet, North and South Carolina (Chasten 1992, Chasten and Seabergh 1992).

(d) Murrells Inlet, South Carolina (Douglass 1987).

(e) Manasquan Inlet, New Jersey (Bruno, Yavary, and Herrington (1998).

(f) St. Marys Entrance, Florida and Georgia (Kraus, Gorman, and Pope 1994, 1995).

(g) East Pass, Florida (Morang 1992a).

(h) Port Mansfield Channel, Texas (Kieslich 1977).

(3) Weirs and other structures and their effects on sediment movement in and around inlets are discussed in Part V-6.

h. Case study of inlet formation and growth: Shinnecock Inlet, Long Island, New York.[1]

(1) Background and inlet breaching (1938).

(a) Shinnecock Inlet is located on the south shore of Long Island, 136 km east of New York Harbor. It is the easternmost of six inlets that cut the south shore barrier islands and allow boat passage between the Atlantic Ocean and the coastal bays. The present inlet was breached during the Great New England Hurricane of 21 September 1938. Inlets had periodically existed in this area before, but immediately before the 1938 hurricane, the barrier was intact and there was a paved road along the beach (Nersesian and Bocamazo 1992) (Figure IV-3-25).

(b) The first aerial photographs of the new inlet were taken by the U.S. Army Air Corps three days after the hurricane (Figure IV-3-26). The seas had calmed, but the large number of overwash deposits attest to the violence of the storm. All the open breaches in this area trended left of perpendicular to the shoreline trend. Drift was to the east (opposite to the normal prevailing direction) because spits had grown from west-to-east across the mouths of the new openings. Two months after the hurricane (29 November 1938) an oval ebb-tide delta had already formed in the Atlantic Ocean, and there was a small shoal in Shinnecock Bay, showing the initial development of a flood shoal (Figure IV-3-27).

(c) There are no eye-witness accounts of exactly how this inlet was cut. One possibility is that storm waves from the ocean cut across the barrier. The overwash fans to the left and right of the inlet support this option. The other possibility is that Shinnecock Bay elevated due to rainwater and runoff. This is supported by a water level of 2.2 (7.2 ft) above mlw estimated at the south end of the Shinnecock canal, across Shinnecock Bay from the barrier island (U.S. Army Corps of Engineers 1958)). At a low or narrow place in the barrier, a torrent of bay water might have burst through the dunes and run out to sea, scouring a channel that later widened and became the inlet shown in the photograph. This latter hypothesis seems most likely because, only two months after the storm, a prominent ebb shoal already existed, while there was only minimal deposition in Shinnecock Bay. The ebb shoal likely consisted of sand eroded from the barrier.

(2) Semi-stabilized inlet (1947). After 1938, the inlet migrated steadily to the west. In 1939-40, Suffolk County erected timber pile bulkhead and short groins on the west side of the channel to prevent westward migration (Nersesian and Bocamazo 1992). However, a 1947 photograph shows that the inlet had moved

[1] Condensed from Morang (1999).